Leptons and Charm

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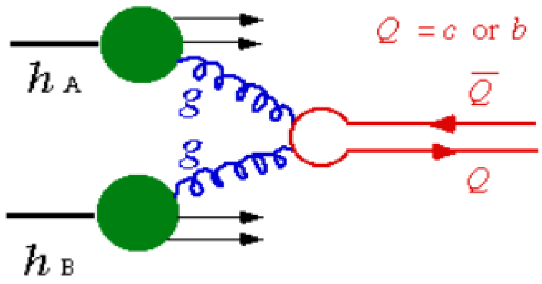
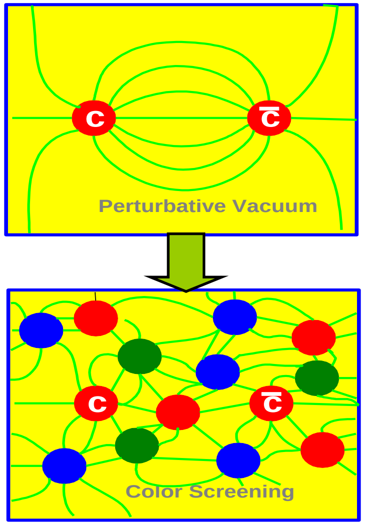
Leading a “Charmed Life”

- Relativistic Heavy Ion (RHI) Collisions intend to produce and study high density matter, the bulk of which is composed of light quarks (u, d, s).
- The charm quark’s mass makes it a rare component (even at RHIC) and thereby yields a unique perspective to the collision dynamics:
  - J/Ψ Suppression.
  - Continuum contribution.
- Thus far in RHI physics, J/Ψ is principally measured through its leptonic decay channels.
- We shall see that at RHIC the charm quark maintains its unique and interesting contribution to our knowledge and insight into collision dynamics.

Role of the Charm Quark

- $c\bar{c}$ pairs are formed most often via gluon fusion.
- J/Ψ results when the $c\bar{c}$ from a single production point pair.



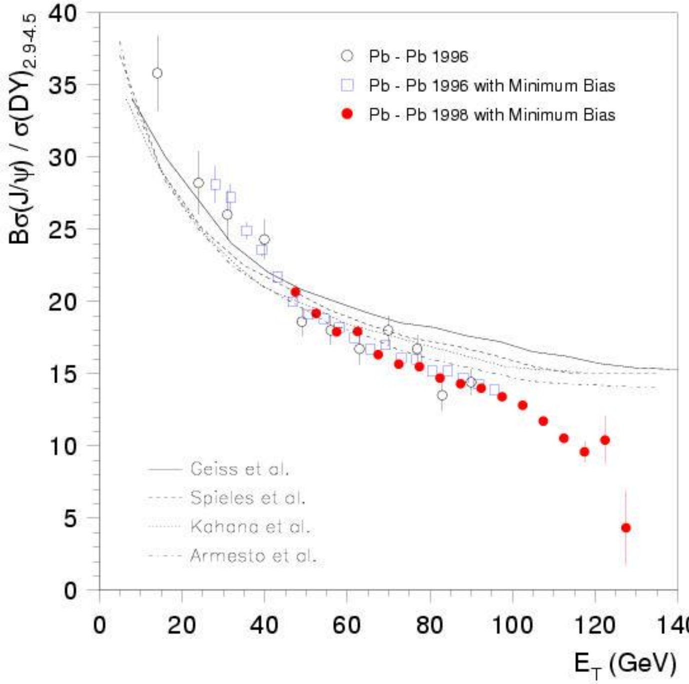


Matsui/Satz Suppression Mechanism

- The J/Ψ finds itself enveloped by the medium and dissolved.
- The rarity of charm quarks makes it unlikely that the find each other at the hadronization stage

Matsui & Satz, Phys. Lett. 176B (1986) 416.

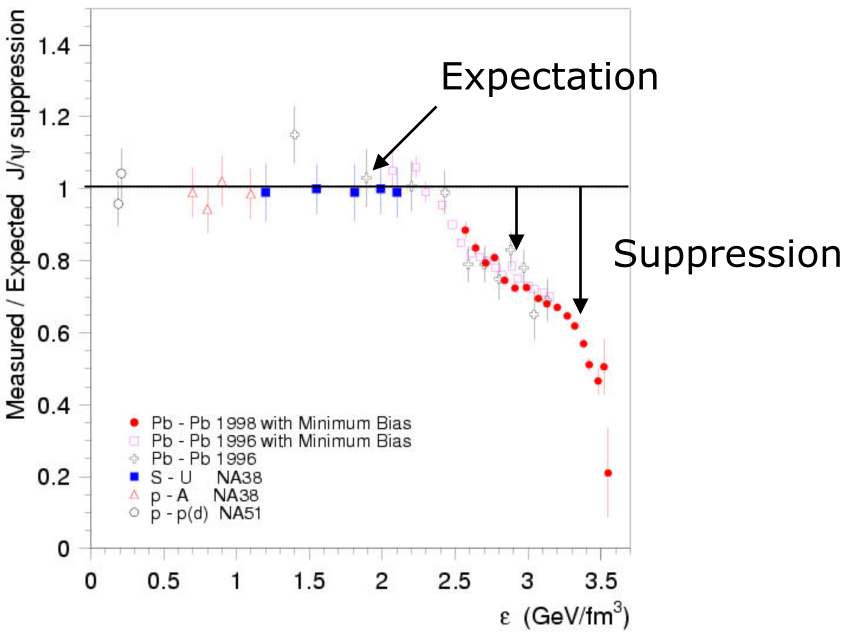
Observations at CERN (NA50)



J/Ψ normalized to Drell-Yan vs "Centrality"

NOTE: D-Y is not the optimal normalization, closed/open charm is better.

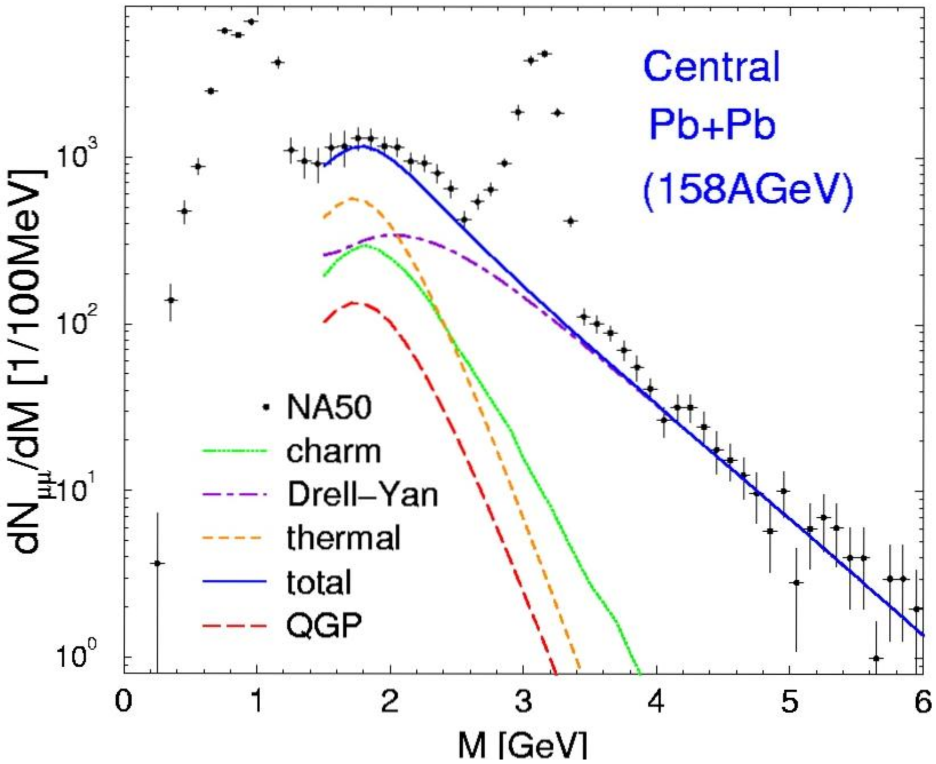
- Pb-Pb collisions show suppression in excess of "normal" nuclear suppression



NA50, Phys. Lett. B477 (2000) 28.

Additional CERN Puzzles

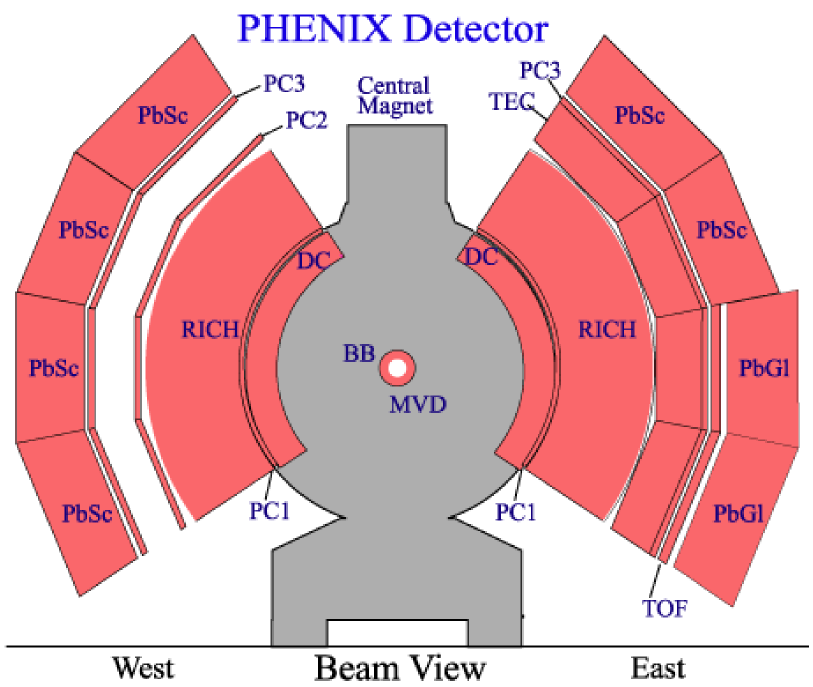
- Excess continuum yield at masses below J/Ψ not fully explained:
  - Enhanced charm?
  - Thermal?
  - QGP?
  - ???



Charm at RHIC

- Charm at RHIC is decidedly less rare than at the SPS energies.
- Indeed the mechanism of dissolution of charm in QGP scenario would likely be complemented by some degree of recombination forming J/Ψ particles.
- The PHENIX experiment was specifically designed to measure J/Ψ production in nucleon-nucleon and nucleus-nucleus collisions.

PHENIX Central Arms (Electron Measurements)



- High resolution tracking and momentum measurement from Drift Chamber. Matching with Pad Chambers.
- Good electron identification from Ring Imaging Cherenkov detector and Electromagnetic Calorimeter.
- High performance Level-1/Level-2 trigger.

Centrality selection with Beam -Beam Counters and Zero-Degree Calorimeters.

Measure electrons between $|\eta|<=0.35$ and $p >=0.2GeV$

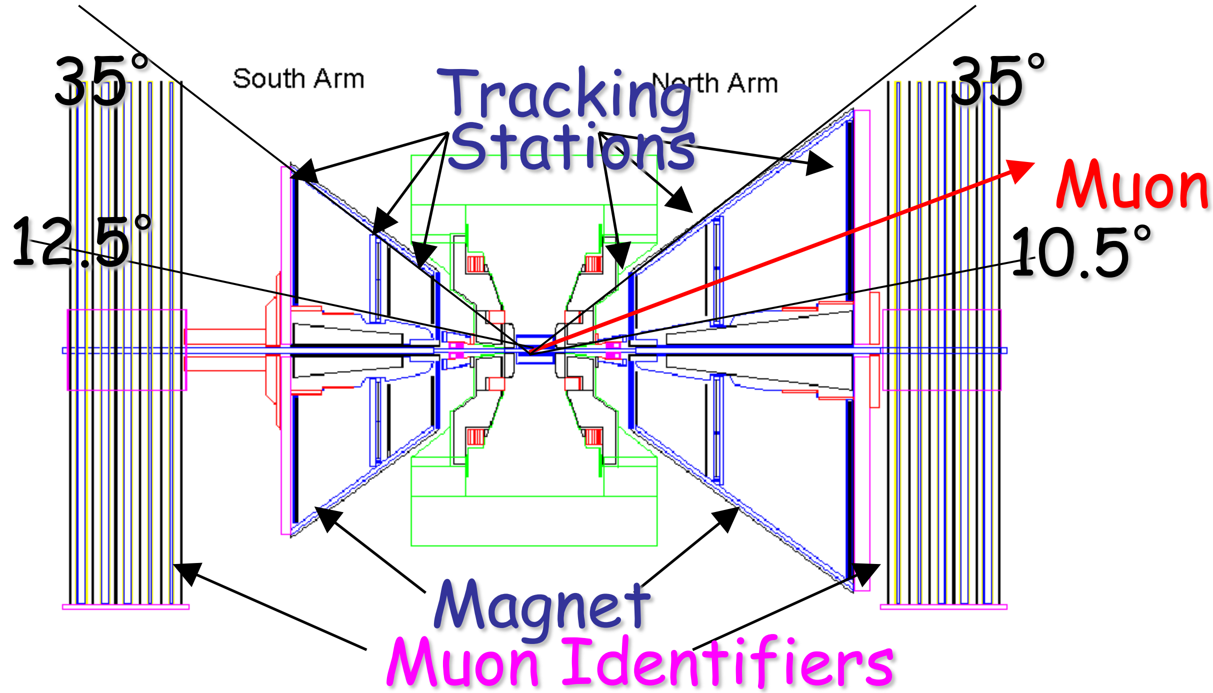
PHENIX Muon Arms (Muon Measurements)

2 Muon Trackers = 2x3 stations

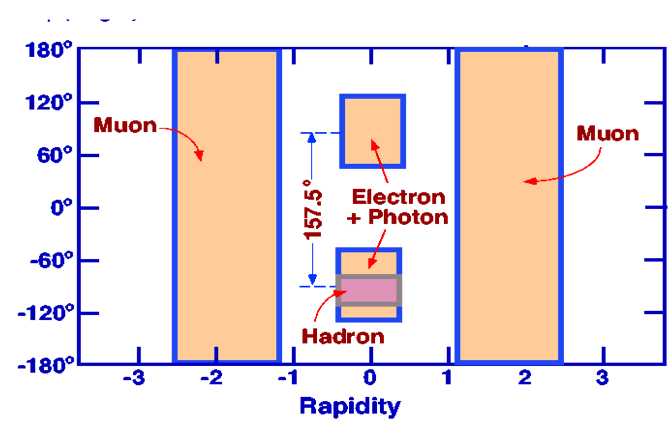
2 Muon Identifiers = 2x5 planes

South Arm:
Began operations in 2001: Run-2.

North Arm:
Installed in 2002.

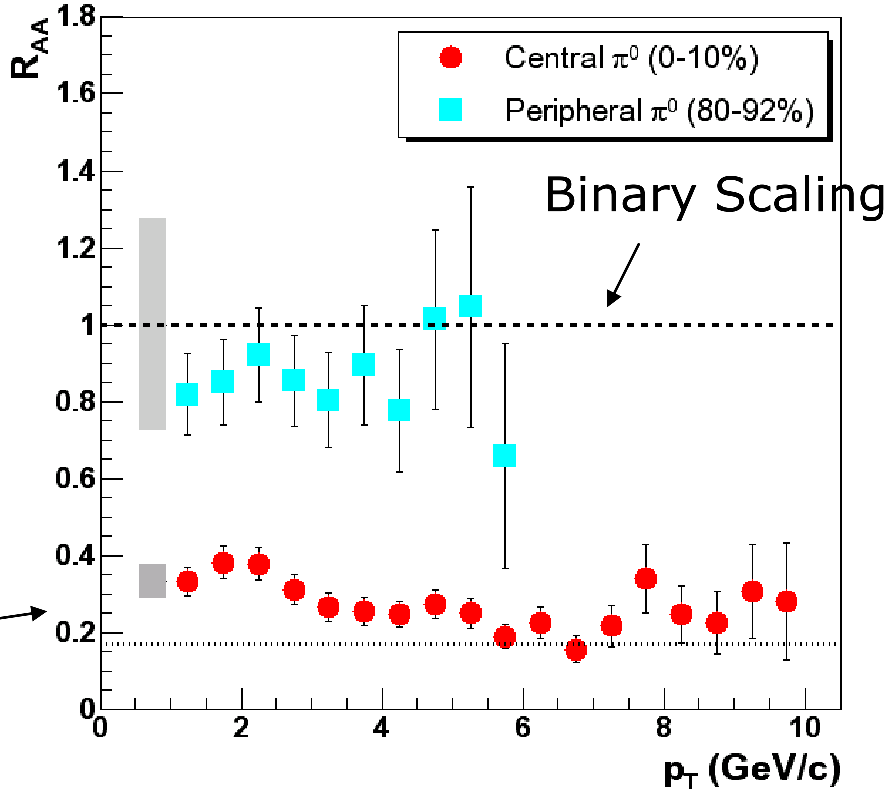


Acceptance : $1.2 < |\eta| < 2.4$
$\Delta\Phi = 2\pi$
Muon minimum momentum ~ 2 GeV/c



Today's Context

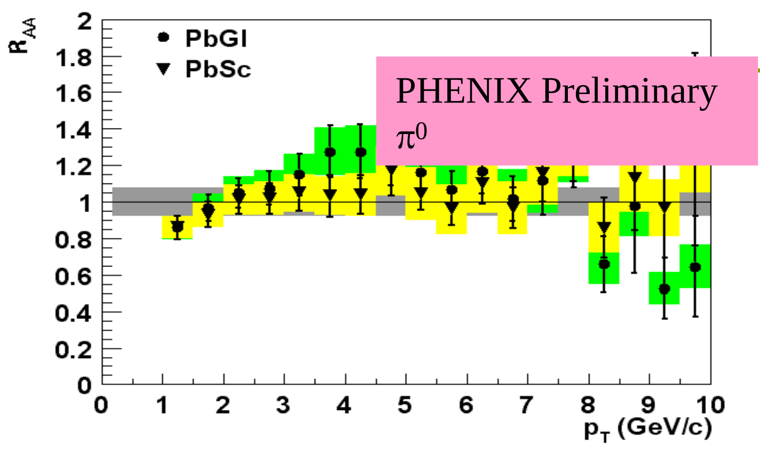
- Exciting results from AuAu collisions indicate particle production at high transverse momentum scales slower than the number of binary collisions.
- 3-5X suppression.
- d-Au preliminary results make the AuAu results even more intriguing.

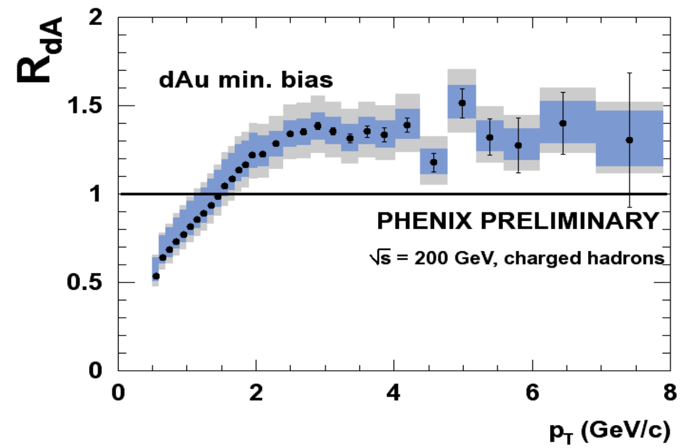


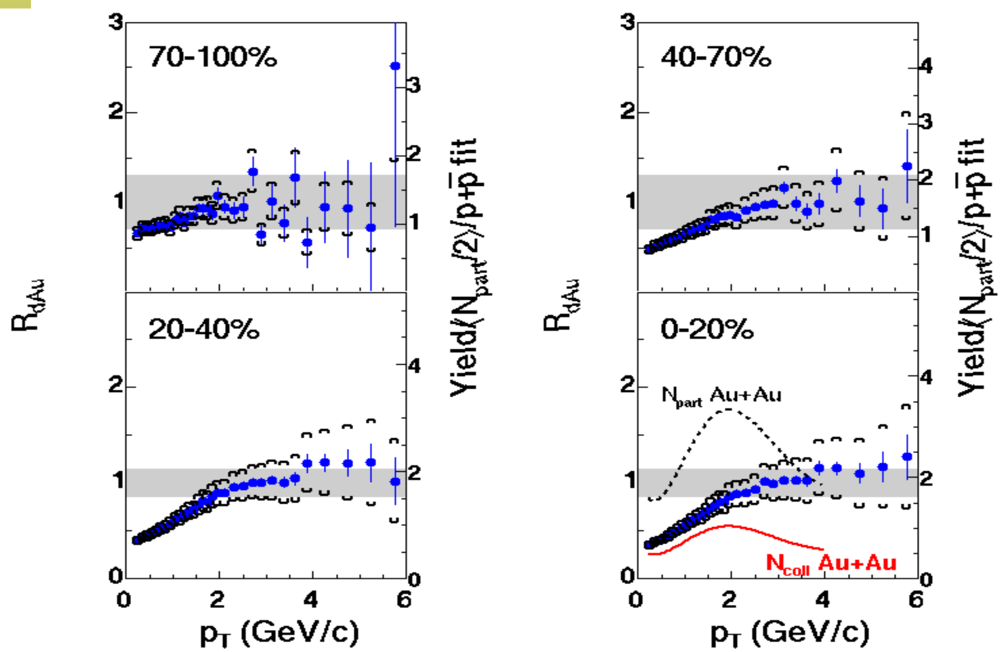
Is charm similarly suppressed?

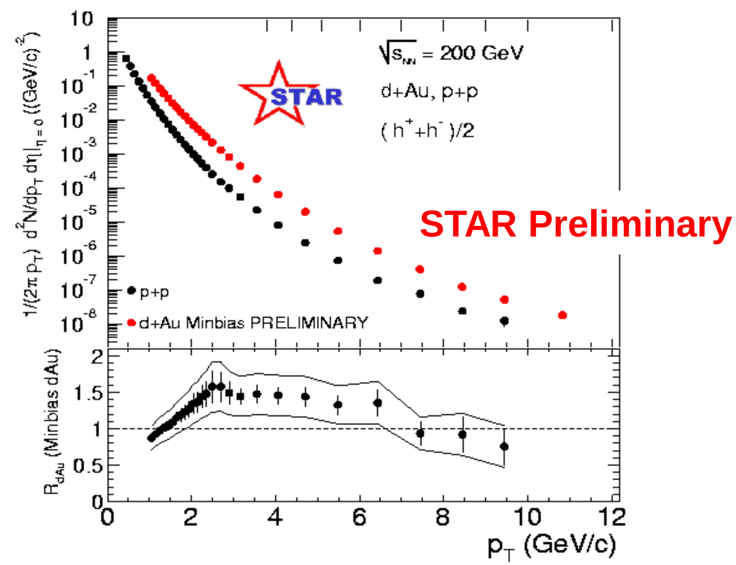
If yes--why?; If no--why not?

Hot Data



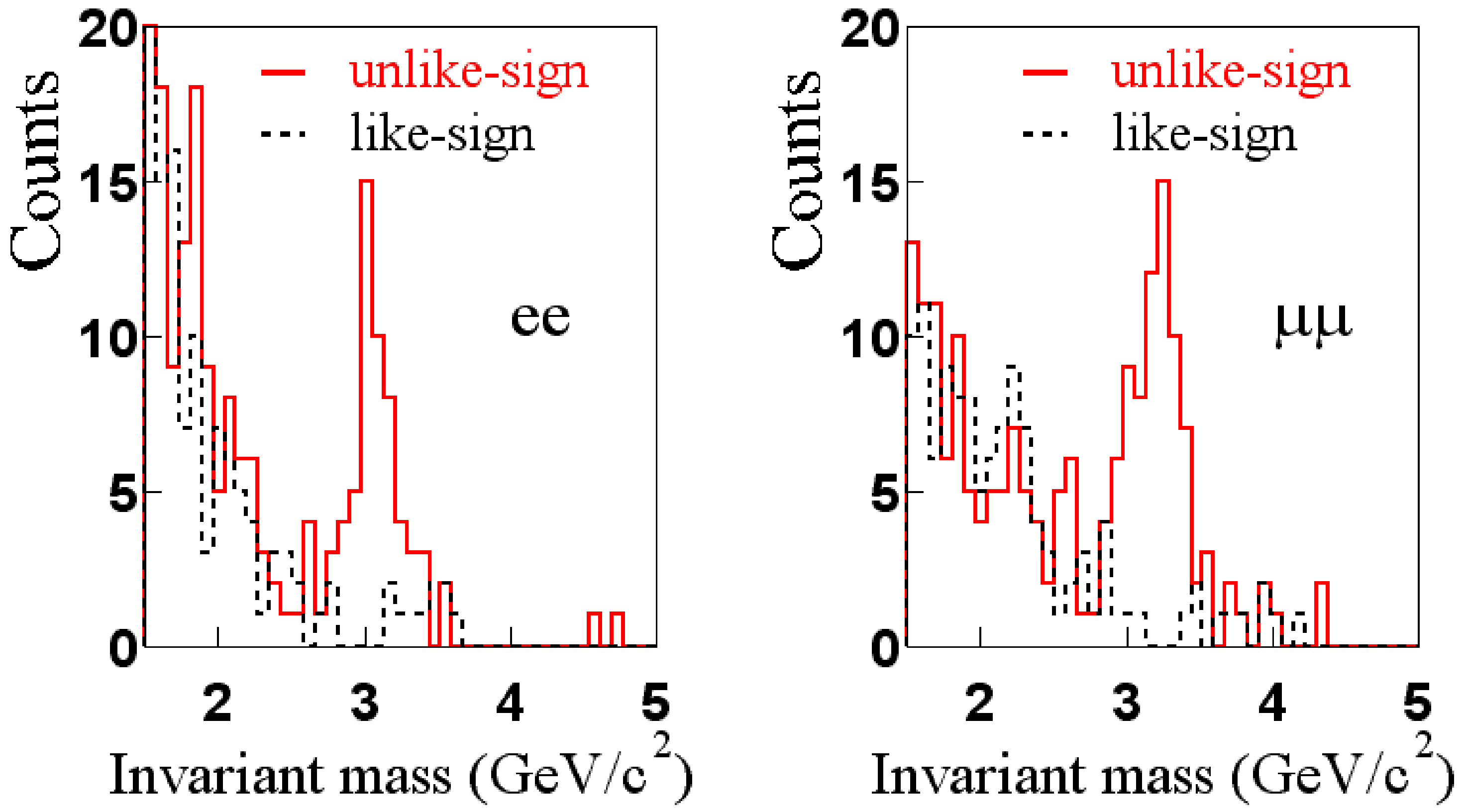






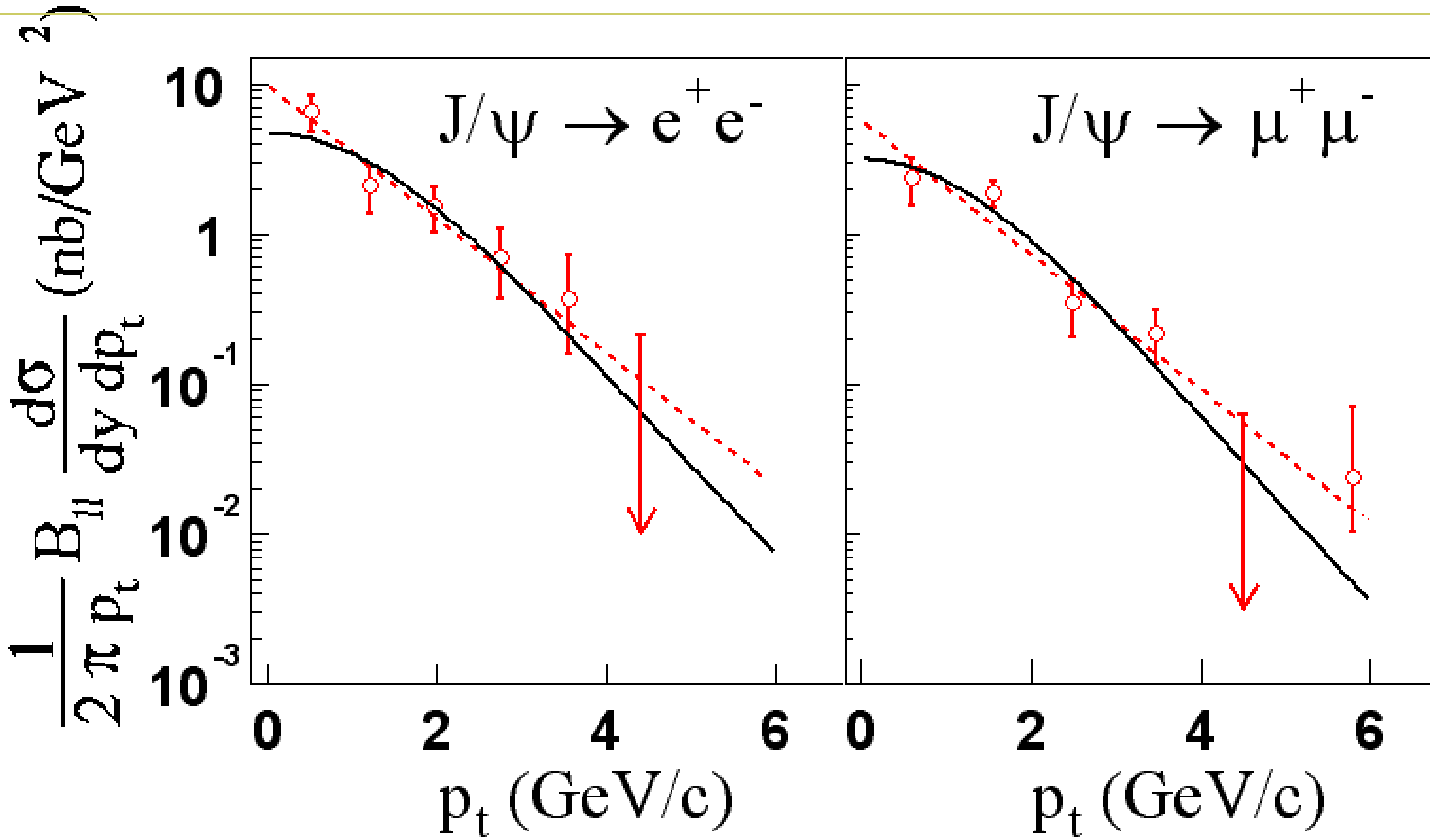
How about the Charm quark?

Establishing pp baseline--J/Ψ



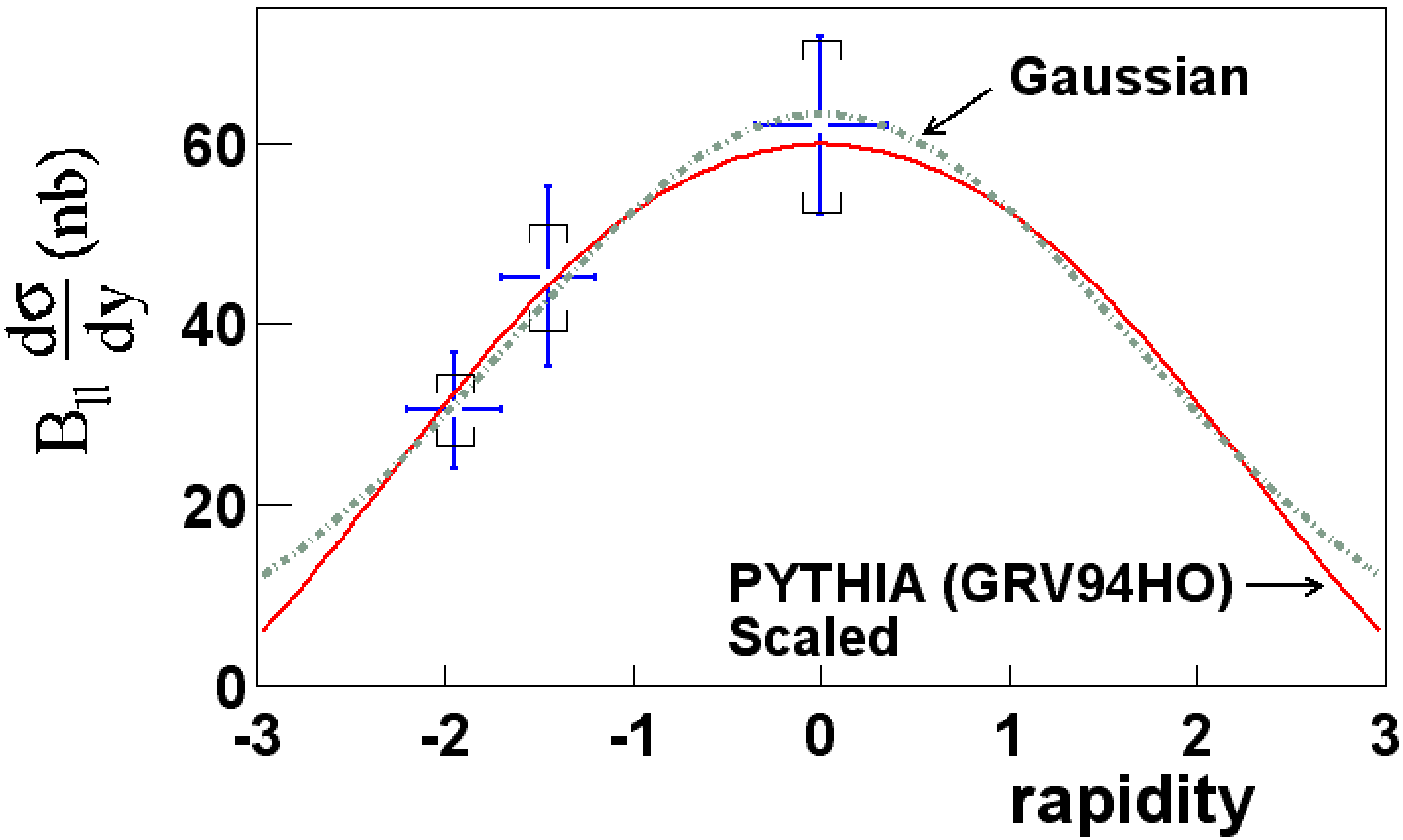
Clear J/Ψ signals seen in both central and muon arms.
Resolutions in agreement with expectations.

pp--Transverse Momentum Distribution



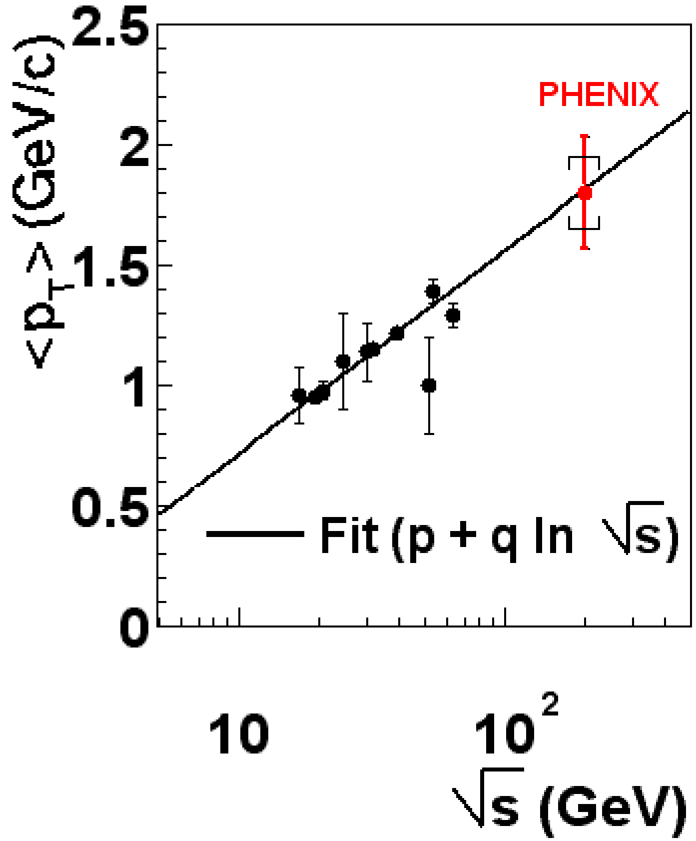
Combination of electron and muon results and phenomenological and exponential fits gives:
$\langle p_T \rangle$ = 1.80 ± 0.23 (stat) ± 0.16 (sys) GeV/c

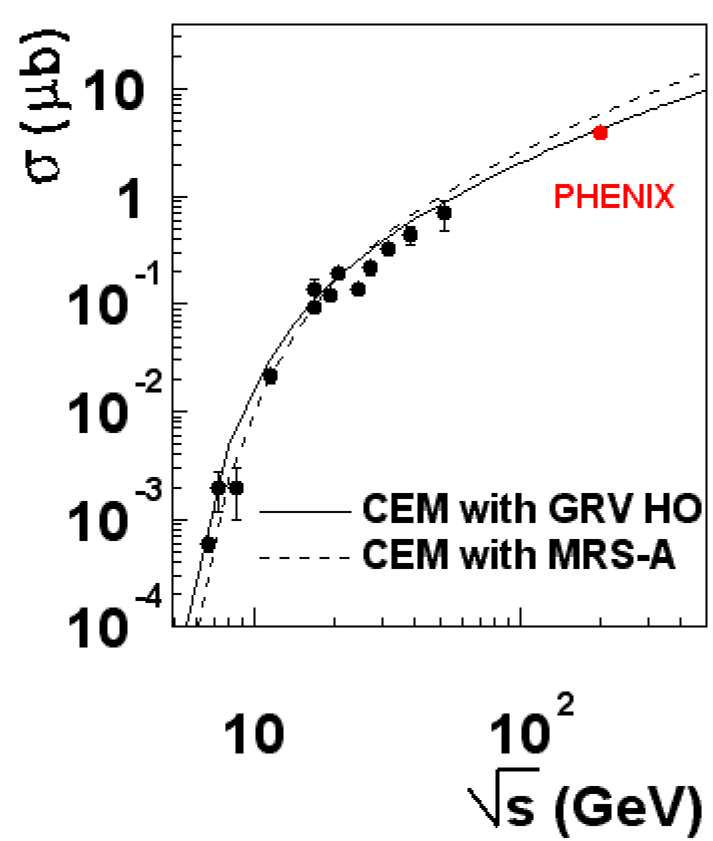
Rapidity Distribution



Integrated cross-section : 3.98 ± 0.62 (stat) ± 0.56 (sys) ± 0.41(abs) μb
Estimated B decay feed down contribution : < 4% (@ 200 GeV)

Comparison to Other Experiments



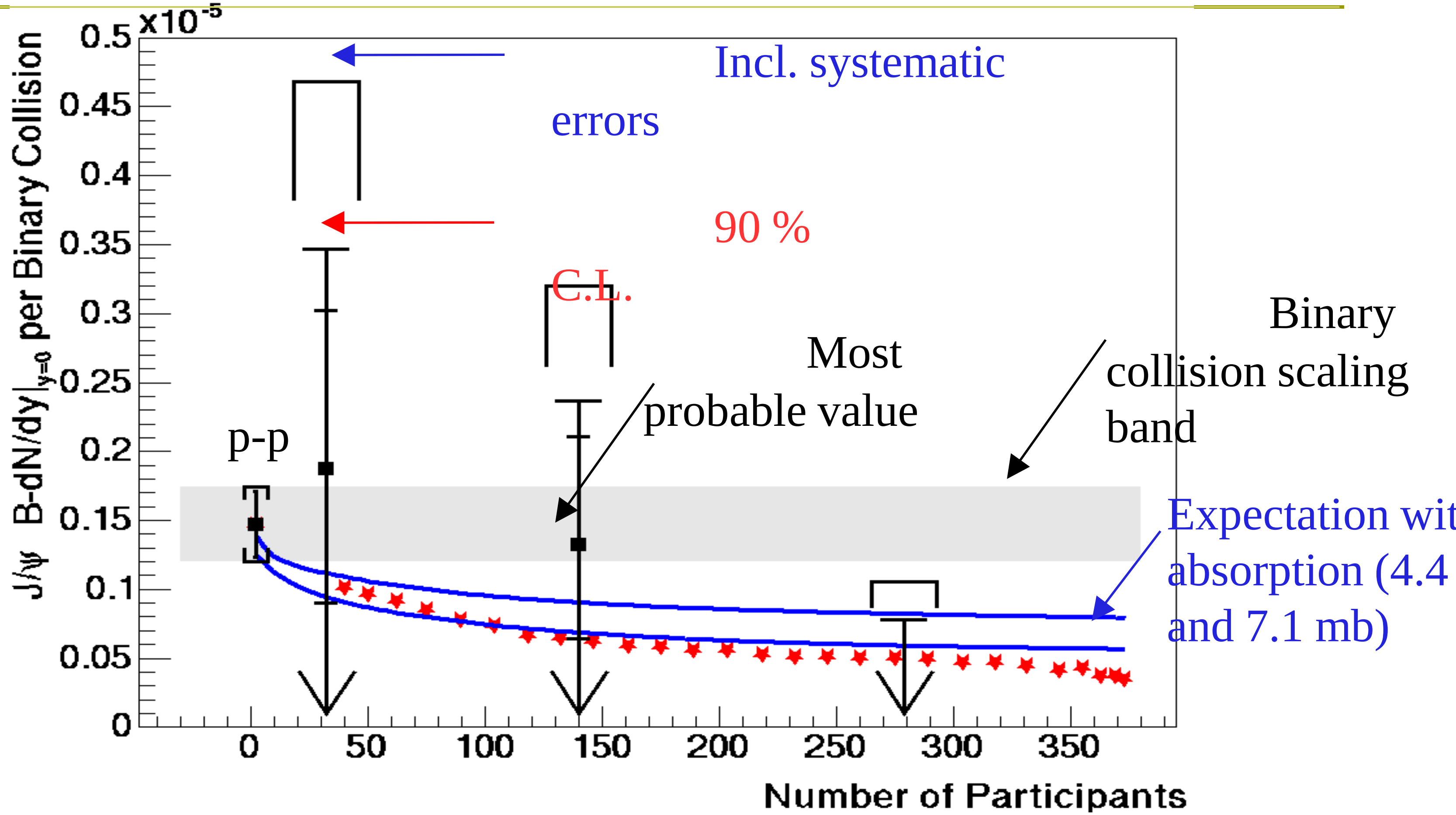


Phenomenological fit for average p_T; p = 0.531, q= 0.188
Cross-section well described by Color Evaporation Model.

Baseline Established

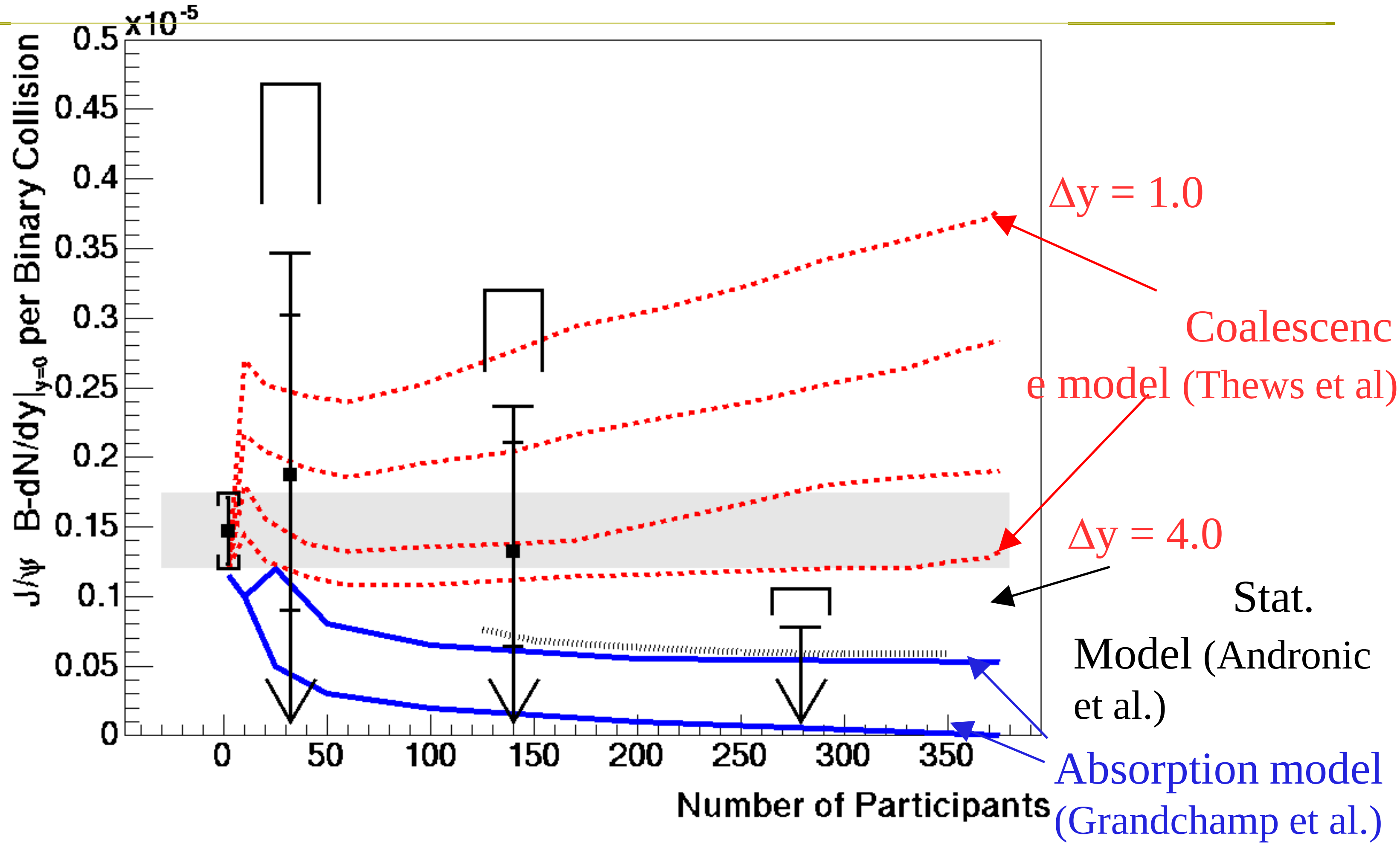
- pp J/Ψ results are of small statistics, but nonetheless are consistent with simple Pythia calculations.
- pp J/Ψ results follow smoothly upon lower $\sqrt{s}$ data and phenomenological extrapolations.
- Higher Statistics will be necessary to establish a baseline of sufficient precision to identify a suppression of the same magnitude as NA50.
- Detailed measurements of d-Au collisions (data on tape) will be used to establish "normal" nuclear suppression pattern.

Run-2 AuAu Statistics are Poor



NA50 points normalized to pp point

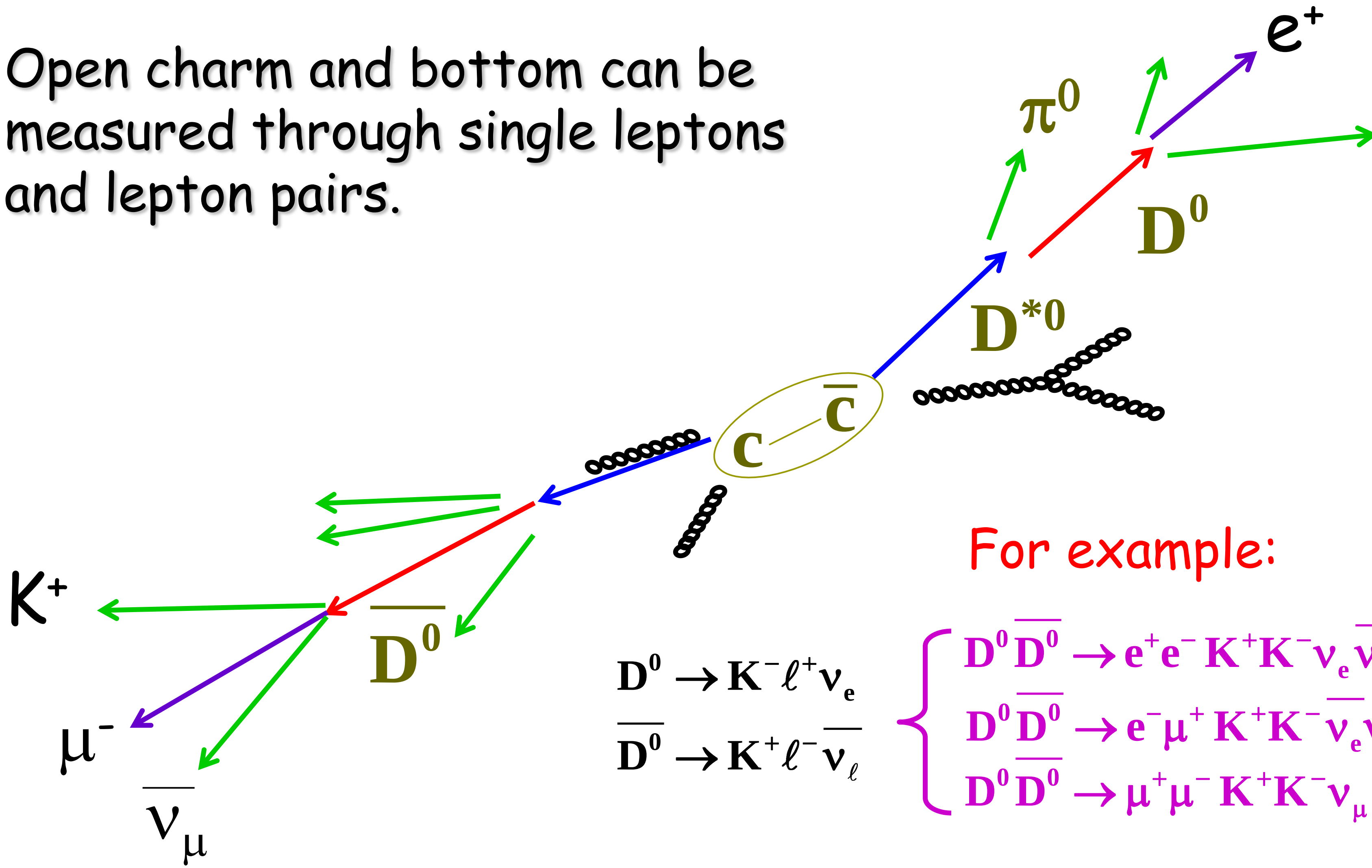
“Enhancement” Models Disfavored



Disfavor models with enhancement relative to binary collision scaling. Cannot discriminate between models that lead to suppression.

Open Charm via Semi-Leptonic Decays

Open charm and bottom can be measured through single leptons and lepton pairs.



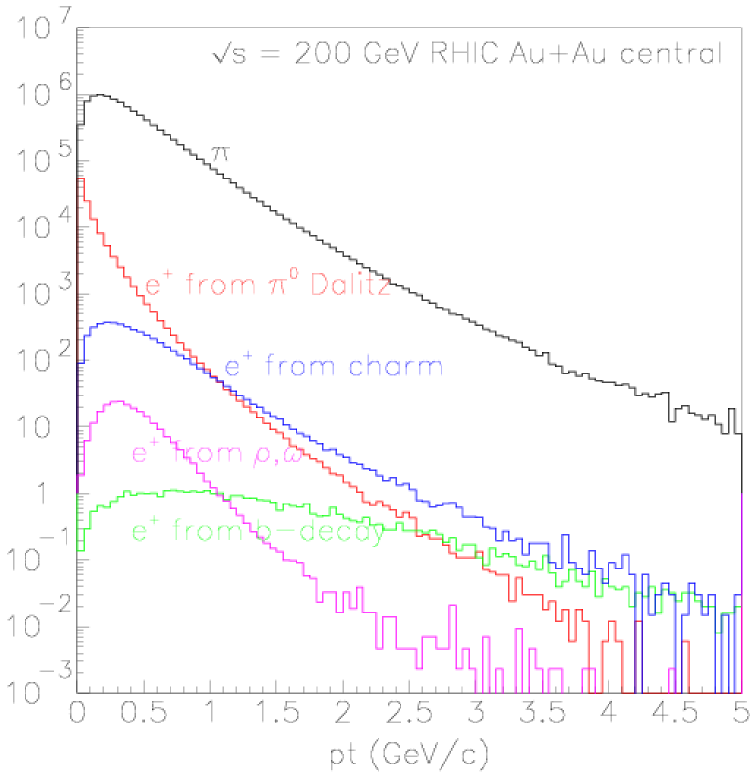
$$D^0 \to K^- \ell^+ \nu_e$$

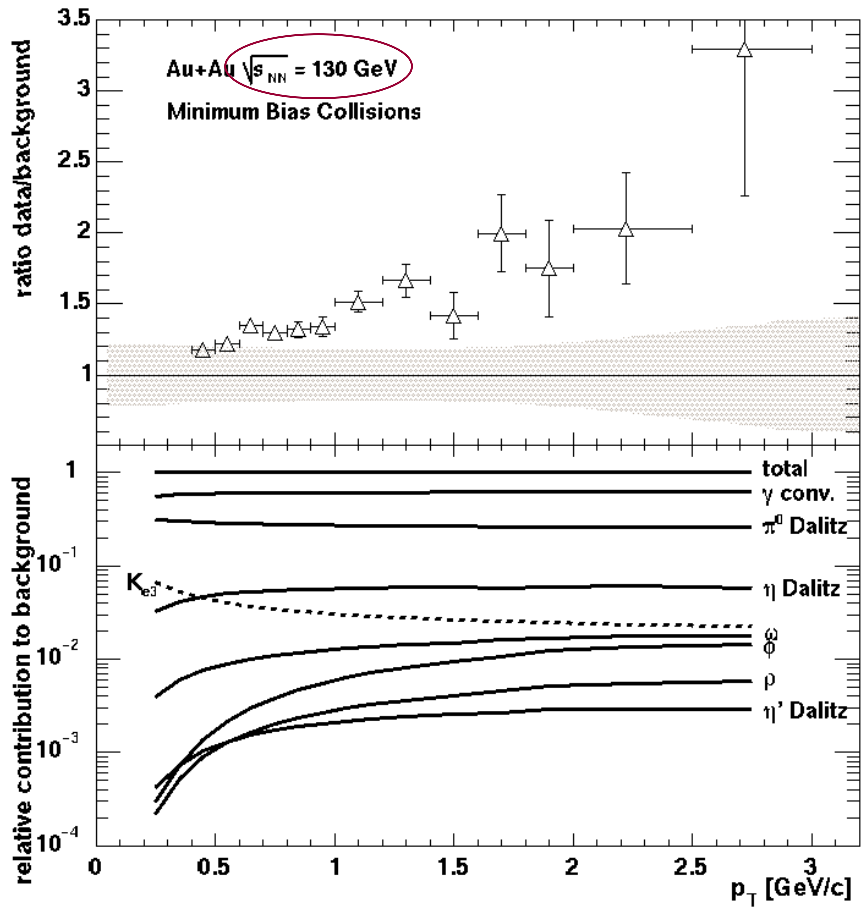
$$\bar{D}^0 \to K^+ \ell^- \bar{\nu}_\ell$$

For example:

$$\begin{cases} D^0\bar{D}^0 \to e^+ e^- K^+ K^- \nu_e \bar{\nu}_e \\ D^0\bar{D}^0 \to e^- \mu^+ K^+ K^- \bar{\nu}_e \nu_\mu \\ D^0\bar{D}^0 \to \mu^+ \mu^- K^+ K^- \nu_\mu \bar{\nu}_\mu \end{cases}$$

Inferring Charm Production—Method I





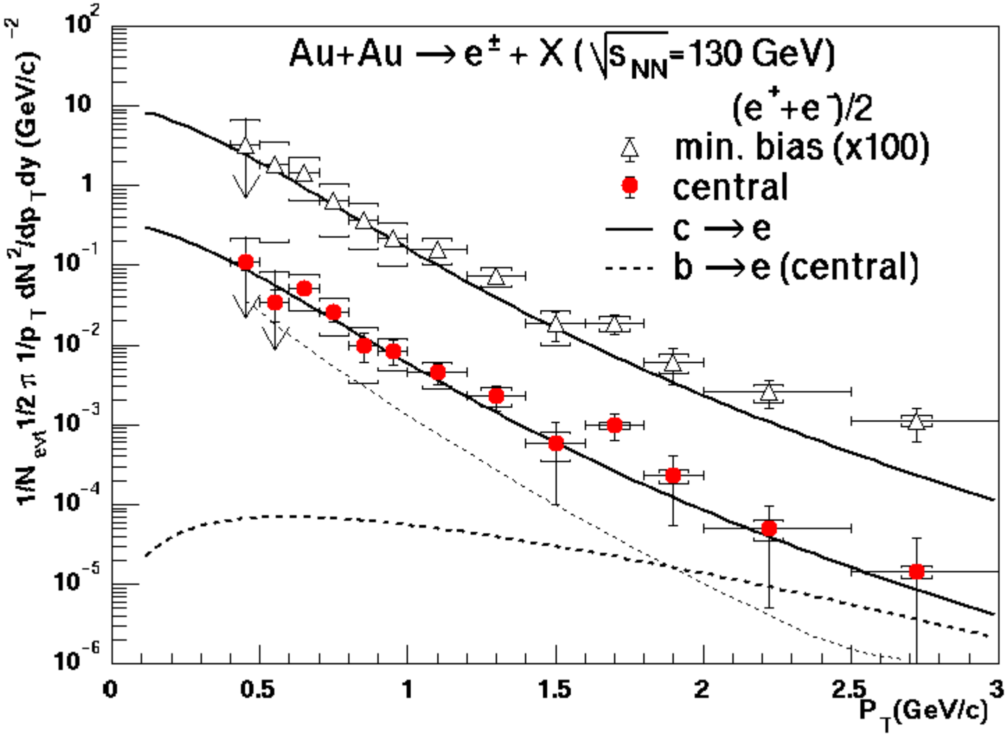
- Use data (where available) to establish "cocktail" of electron sources.
- Subtract these sources from the data.
- Attribute excess to open charm

• Dominated by measured π^0 and γ conversions.

PHENIX, PRL 88 192303 (2002)

Electron Spectra at 130 GeV

- Compare inferred yield to binary scaling of Pythia open-charm calculations.
- Excellent agreement to Pythia in min-bias AND central collisions!!
- Where is the high-p_T suppression of the charm quarks?



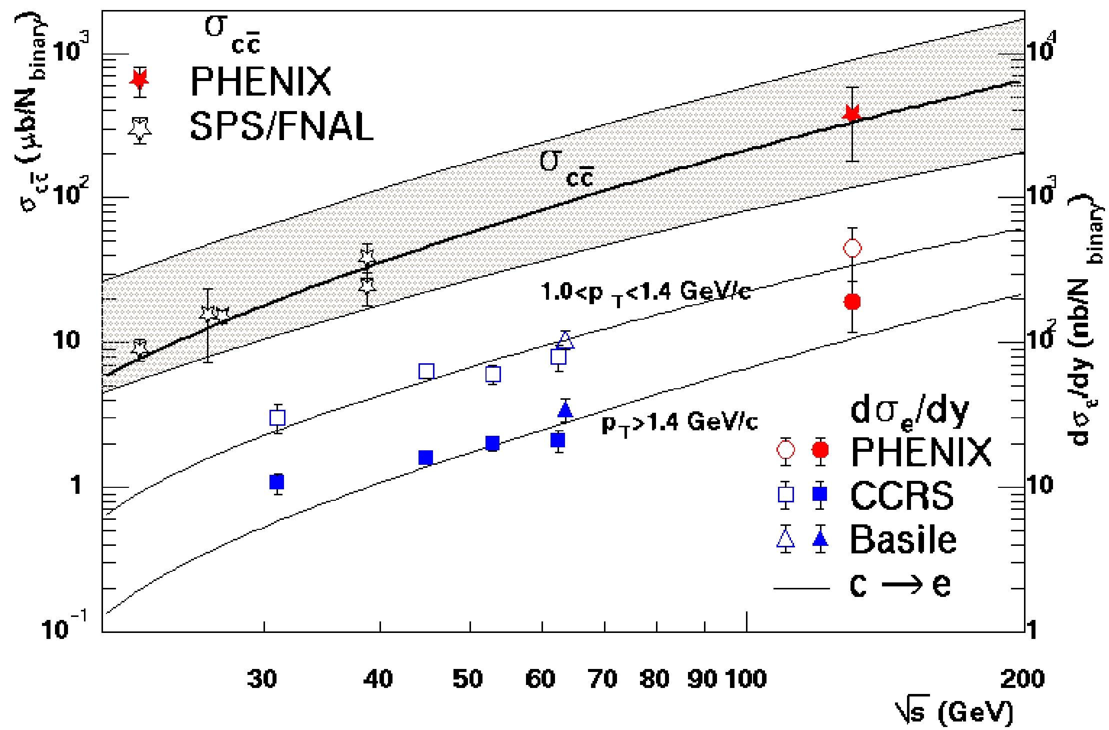
NOTE: Pythia comparison is on absolute scale, no free parameters.

Systematic Trends with Collision Energy

Single electron cross sections and charm cross sections are compared with

Solid curves: PYTHIA

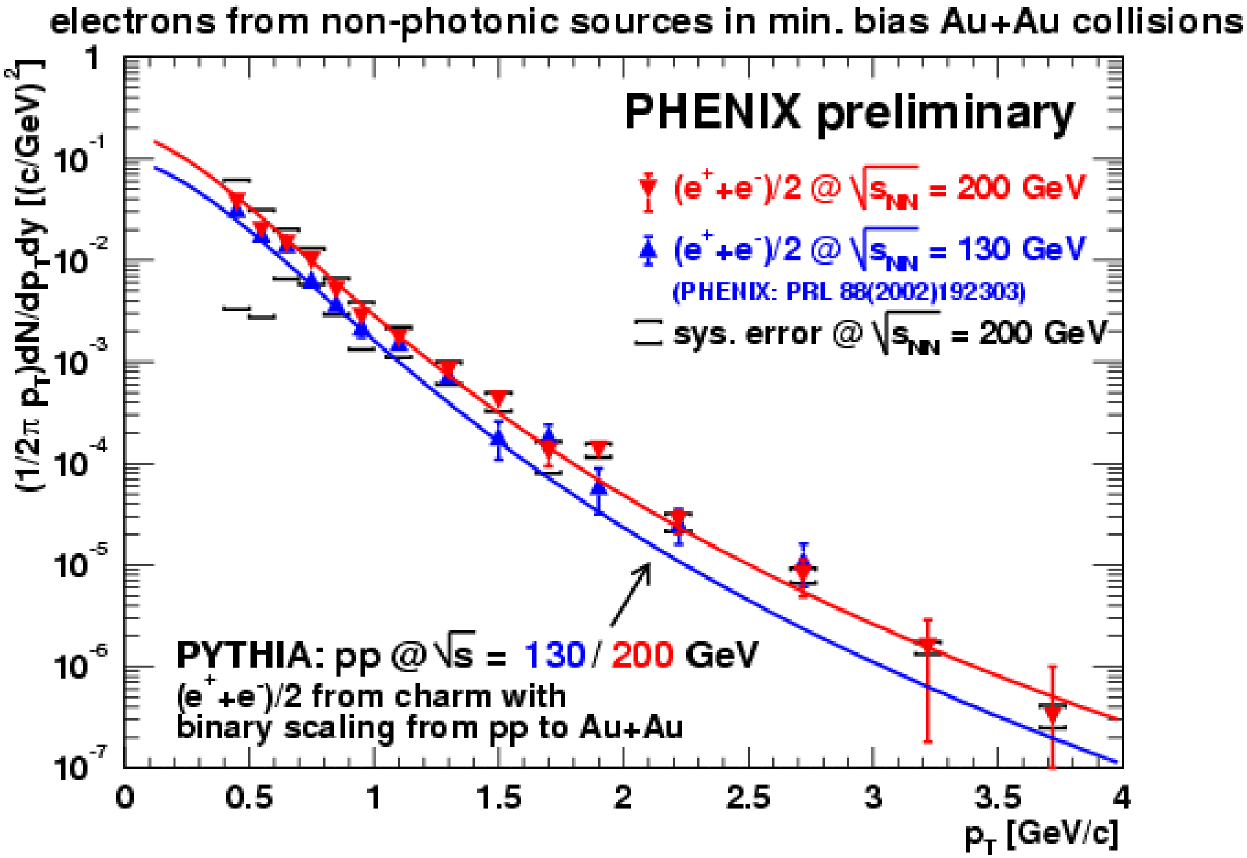
Shaded band: NLO QCD



Assuming binary collision scaling, PHENIX data are consistent with √s systematics (within large uncertainties).

Inferring Charm II (200 GeV)

- Virtual photon sources are also real photon sources.
- Measure the real photon spectrum by adding photon convertor to PHENIX.
- Subtract the photon spectrum from the total to produce “non-photonic source spectrum.



The yield of non-photonic electron at 200 GeV is higher than 130 GeV

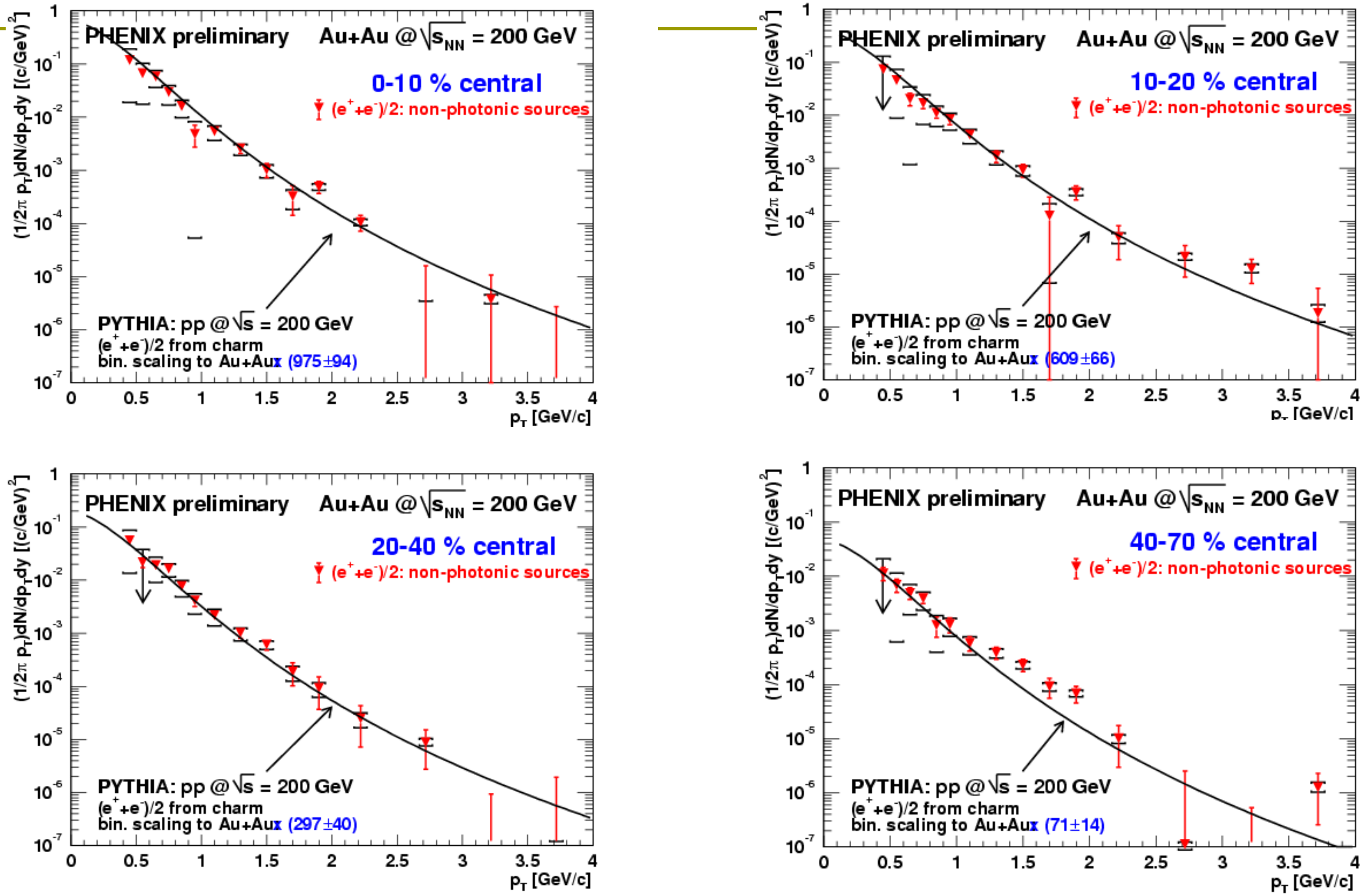
The increase is consistent with binary-scaled PYTHIA charm calculation

(σ_{cc} (130 GeV) = 330 μb, σ_{cc} (200 GeV) = 650 μb)

Large systematic uncertainty due to material thickness without converter.

The error will be reduced in the final result.

Charm Centrality Dependence.



PHENIX data consistent with the PYTHIA charm spectrum scaled by number of binary collisions in all centrality bins!

The "Charmed" Life

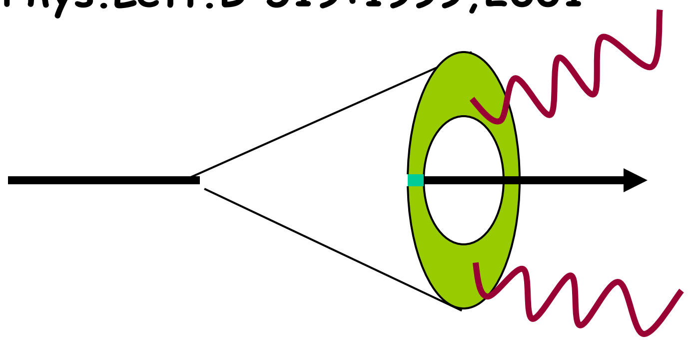
- In contrast to the light quark suppression, the charm quark spectra seem unaffected by any energy loss.
- Ironically, agreement with simple scaling laws is now the source of intrigue.
- Several mechanisms are proposed to explain the apparent non-suppression of the heavy charm quark.

#1: Dead Cone Effect ??

Dead Cone effect :

- Gluon radiation from a massive parton is suppressed at angles $\theta < Mq/Eq$ (manifestation of causality as $\upsilon_Q < c$)

D. Kharzeev et al. **Phys.Lett.B 519:1999,2001**



- The slower moving quark also samples a more dilute density profile as the medium expands

$\rightarrow$ reduced energy loss ΔE

$\rightarrow$ is ΔE inhibited enough for produced medium to be transparent to heavy quarks ($\lambda_Q > L_N$) ?

#2: Hydrodynamic Flow of Charm ??

- Low and medium p_t (0-4 GeV) D may be formed inside fireball and rescattering with surrounding particles may lead to collective behavior.

  Interactions with other hadrons are relatively weak $\sigma(\pi D)$~10 mb

  (Ziwei Lin, C. M. Ko, Bin Zhang, Phys. Rev. C 61, 024904 (2000).
  Ziwei Lin, C. M. Ko, Bin Zhang, preprint [nucl-th/9905007])

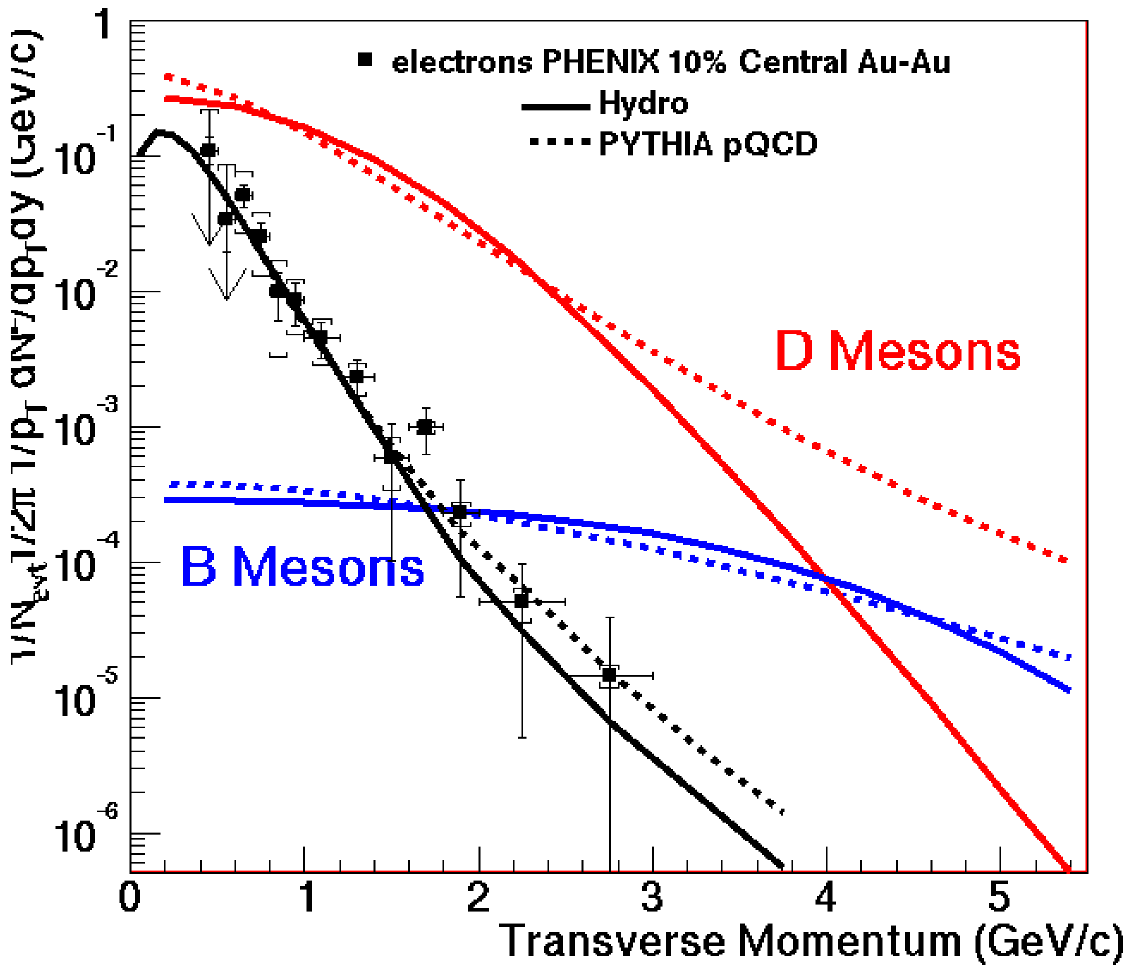
  However there is an abundance of π

or

  Charm quarks undergo significant scattering in partonic medium and participate in hydrodynamic type expansion then either fragment into D mesons or coalesce with commoving spectators of low relative momentum to form D mesons.

⇒Thermalization, hydrodynamic flow of D?

Flowing D Meson Calculation.



Electon data are consistent with both:

1. Medium transparent to heavy quarks which then fragment into D/B mesons outside the system (scaled Pythia)

2. Highly opaque medium with charm boosted via rescattering and hadronizing in the system

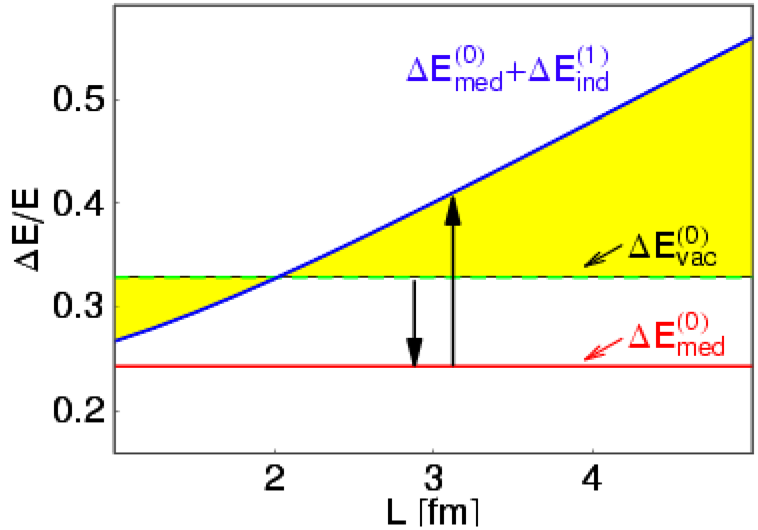
J. Nagle, S. Kelly, M. Gyulassy, S.B. JN, Phys. Lett. B 557, pp 26-32.

#3: Dynamical Gluon Mass in Plasma ??

M. Djordjevic and M. Gyulassy calculations indicate that the "dead cone" effect is not enough to explain the PHENIX heavy quark behavior. ($\Delta E/E \sim 0.2$)

Analog of Ter-Mikayelian effect:
Polarization of the QCD medium leads to disperion relation for radiated gluons that can be approximated by introducing an effective gluon mass m_g.

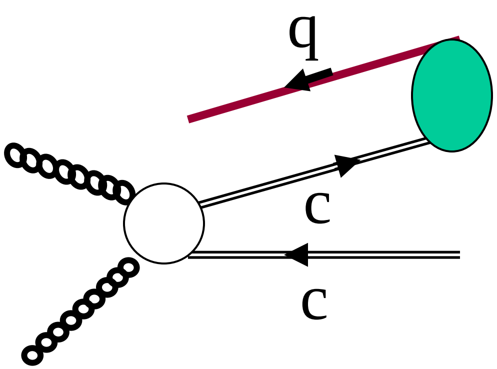
Dynamical m_g suppresses the radiation of soft gluons ($\omega < \omega_{pl}$)
$\Rightarrow$ The net energy loss could be close to the vacuum value



M. Djordjevic and M. Gyulassy nucl-th:0302069

#4: Quark Coalescence ??

Quarks/antiquarks in a densly populated phase-space can form hadrons via recombination and not via fragmentation
(~ overlap of hadron wavefunction and partons distribution)



Hadron emission from thermal parton ensemble may be dominated by parton recombination (hadronization inside the medium)

For medium p_T (< 5 GeV) suppression due to radiation may be counteracted by recombination mechanism

For high p_T fragmentation dominates hadron production (partons fast enough to escape medium)

S. Bass et al. nucl-th/0301087

Summary

- Charm continues to be a fascinating and rich observable at RHIC energies.
- pp and dAu J/Ψ measurements establish baseline for AuAu J/Ψ production.
  - pp will benefit from ongoing run.
  - dAu in the can.
- Present J/Ψ measurements disfavor strong enhancement scenarios.
- Open charm seems, within large errors, to not exhibit the high p_T suppression prevalent in the light quarks.
- High Statistics AuAu data will provide:
  - Resolution to charm flow question.
  - Measurement of J/Ψ rates.